

The Astronomical Low Frequency Array: A Proposed Explorer Mission for Radio Astronomy

D. Jones¹, R. Allen², J. Basart³, T. Bastian⁴, J.-L. Bougeret⁵, B. Dennison⁶, M. Desch⁷, K. Dwarkanath⁸, W. Erickson⁹, D. Finley⁴, M. Kaiser⁷, N. Kassim¹⁰, T. Kuiper¹, R. MacDowall⁷, M. Mahoney¹, R. Perley⁴, R. Preston¹, M. Reiner⁷, P. Rodriguez¹⁰, R. Stone⁷, S. Unwin¹, K. Weiler¹⁰, G. Woan¹¹, & R. Woo¹

¹ Jet Propulsion Laboratory, California Institute of Technology, USA

² Space Telescope Science Institute, USA

³ Iowa State University, USA

⁴ National Radio Astronomy Observatory, USA

⁵ Observatoire de Paris, France

⁶ Virginia Polytechnic Institute, USA

⁷ Goddard Space Flight Center, USA

⁸ Raman Research Institute, India

⁹ University of Maryland, USA, and University of Tasmania, Australia

¹⁰ Naval Research Laboratory, USA

¹¹ University of Glasgow, UK

Abstract

A radio interferometer array in space providing high dynamic range images with unprecedented angular resolution over the broad frequency range from 0.03 - 30 MHz will open new vistas in solar, terrestrial, galactic, and extragalactic astrophysics. The ALFA interferometer will image and track transient disturbances in the solar corona and interplanetary medium - a new capability which is crucial for understanding many aspects of solar-terrestrial interaction and space weather. ALFA will also produce the first sensitive, high-angular-resolution radio surveys of the entire sky at low frequencies. The radio sky will look entirely different below 30 MHz. As a result, ALFA will provide a fundamentally new view of the universe and an extraordinarily large and varied science return.

1. SCIENTIFIC GOALS

1.1. Introduction

The Astronomical Low Frequency Array (ALFA) mission will produce the first low frequency, high resolution radio images of the solar corona and interplanetary disturbances such as shocks driven by coronal mass ejections (CMEs). Equally important, for the first time we will be able to image and track these solar disturbances from the vicinity of the sun all the way to 1 AU, which requires observing frequencies from tens of MHz to tens of kHz. Since Earth's ionosphere severely limits radio interferometry from the ground at frequencies below ~ 30 MHz, these measurements must be made from space. The ALFA imaging interferometer will operate from 0.03 to 30.0 MHz.

One of the major space weather goals of the ALFA mission is accurate prediction, days in advance, of the arrival of CMEs at Earth. CMEs interacting with Earth's magnetosphere can result in geomagnetic storms which are capable of damaging satellite and electric utility systems and disrupting communications and navigation services. Solar disturbances can also pose a threat to astronauts. For this reason, successors to ALFA may become as indispensable for future space weather forecasting as weather satellites are today. ALFA will be launched shortly after solar maximum when some of the most energetic solar disturbances are expected. In addition, ALFA will image Earth's magnetospheric response to such solar disturbances, providing a unique global view of the magnetosphere from the outside.

The ALFA mission will also produce the first sensitive, high resolution radio images of the entire sky at frequencies below 30 MHz - a region of the spectrum that remains unexplored with high angular resolution. Many physical processes involved in the emission and absorption of radiation are only observable at low radio frequencies. For example, the coherent emission associated with electron cyclotron masers, as seen from the giant planets, Earth, and several nearby stars, is not only expected to occur and be detectable elsewhere in the galaxy but to be ubiquitous. Incoherent synchrotron radiation from fossil radio galaxies will be detectable by ALFA, revealing the frequency and duration of past epochs of galactic nuclear activity. It is also likely that unexpected objects and processes will be discovered by ALFA. Indeed, one of the exciting aspects of the mission is its very high potential for discovery.

Because the solar and extra-solar-system astrophysics programs are managed separately within the NASA Office of Space Science, we discuss their science goals separately in this paper. However, it should be kept in mind that ALFA will simultaneously address key goals in both the Sun-Earth Connection (SEC) and Structure and Evolution of the Universe (SEU) science theme areas with no significant increase in cost or compromise in mission design.

In the SEC area, our science goals address:

- solar variability - physics of solar transient disturbances, the evolution of coronal and solar wind structures, and interactions of plasma and magnetic field topology.
- terrestrial response - solar interactions with Earth's magnetosphere, geomagnetic storms, and space weather.

- implications for humanity - forecast the arrival of coronal mass ejections.

In the SEU theme area, ALFA will address:

- galaxy evolution - detection of fossil radio galaxies and very-high-redshift radio galaxies, and cosmic ray diffusion times and magnetic field distributions in galaxies.
- life cycles of matter - distribution of diffuse ionized hydrogen in the interstellar medium, energy transport via interstellar plasma turbulence, origin of cosmic ray electrons, and the detection of old galactic supernova and gamma-ray remnants.
- discover new phenomena and test physical theories - new sources of coherent radio emission, pulsar emission regions, shock acceleration, physics of electrically charged dusty plasmas, and new classes of objects not seen at higher frequencies.

The fundamental technique of ALFA is aperture synthesis, in which interferometric data from a large number of baseline lengths and orientations are combined to produce images with an angular resolution comparable to that of a single aperture the size of the entire interferometer array. This is the basis of ground-based arrays such as the VLA and VLBA and the VSOP space VLBI mission, and results in many orders of magnitude improvement in angular resolution. The concept was endorsed by the radio astronomy panel of the Bahcall (1991) decade review committee, which recommended "...establishing a program of space radio astrophysics during the next decade leading to the establishment of a Low Frequency Space Array, a free flying hectometer wavelength synthesis array for high resolution imaging, operating below the ionospheric cutoff frequency." The technology now exists to carry out this mission inexpensively.

The ALFA imaging interferometer consists of 16 identical small satellites with dipole antennas and low frequency radio receivers, distributed in a spherical array 100 km in diameter. The array will be placed in a nearly circular retrograde orbit 10^6 km from Earth. The size of the array is determined by a fundamental limit to angular resolution created by the scattering of radio waves in the interstellar and interplanetary media. However, this scattering limit is a strong function of direction and observing frequency. To allow for this, it will be possible to vary the size of the array during the mission to increase or decrease the maximum angular resolution.

1.2. The Sun-Earth Connection Science Goals

The study of the nature and evolution of solar transient phenomena is essential to understanding the sun-Earth connection. Transient disturbances traveling through interplanetary space generate radio emissions at the characteristic frequencies of the plasma, which range from a few kilohertz to several gigahertz. The higher frequency emissions occur very close to the sun where the electron density and plasma frequencies are high, while lower frequency emission occurs in the less dense regions far from the sun. Ground-based radio observations are limited by Earth's ionosphere to frequencies above 20 to 30 MHz and therefore to solar emissions that are generated close to the sun ($< 2 R_{\odot}$). For the vast spatial region between the sun and Earth, radio observations from space provide a proven way to observe transients in the sun's extended atmosphere. There

have been numerous space-based radio instruments that have made and continue to make low-frequency observations of the sun. However, without exception, these observations are made with simple dipole antennas from single spacecraft and provide very poor angular resolution. Even the proposed STEREO mission will only use dipole antennas and will consequently only be able to track the centroids of radio bursts.

Meter wavelength Type II bursts have been observed in the solar corona by ground-based observatories since the 1950s, and are associated with coronal shocks (Wagner and MacQueen, 1983). However, kilometric wavelength Type II bursts, which are generated by CME-driven shocks propagating through the interplanetary medium, are observed only by sensitive low frequency spacecraft radio receivers. These interplanetary Type II bursts are associated with the fastest shocks, and the radio emission regions can be very large (Lengyel-Frey and Stone, 1989). As the CME propagates different regions of the shock front become the site of radio emissions and therefore the site of particle acceleration. The Type II radio emission mechanism depends on the local plasma density, so Type II burst observations provide information on plasma density in the vicinity of the shock. Reiner et al. (1998 a,b) demonstrated that kilometric Type II emissions originate in the upstream regions of CME-driven shocks. Images of kilometric Type II bursts obtained by ALFA, at different frequencies, will therefore provide the first high resolution maps indicating the range of densities in the upstream region of CME-driven shocks, and will provide new information about the sites of particle acceleration along the shock front. The temporal and frequency behavior of these type II burst images will enable us to distinguish those CMEs that are directed toward Earth from those that are not. This will permit accurate (to within hours) predictions to be made, days in advance, of their arrival time at Earth.

In addition, ALFA will provide a new, exterior view of Earth's magnetosphere. The ALFA array will be in a near circular orbit about 160 R_E from Earth, providing an ideal opportunity to image Earth's magnetosphere and bow shock from many vantage points over the course of the mission. At the distance of ALFA from Earth, the frontside magnetosphere will subtend 21° and the magnetotail will extend over 40° (Alexander et al. 1979). Bow shock and magnetospheric emissions, while occurring simultaneously, are well separated in frequency and therefore will constitute distinct radio images. Imaging is possible not only on a routine basis as a complement of the IMAGE mission (scheduled for launch in 2000 to observe from within the magnetosphere), but especially when reconnection is occurring on the frontside. These will be the first images of Earth's magnetosphere from the outside and likely the only global images produced during active solar periods.

1.3. The Structure and Evolution of the Universe Science Goals

The multi-frequency, all-sky radio images produced by ALFA will extend our knowledge of phenomena in galactic and extragalactic objects into a vast unexplored spectral region, addressing many SEU goals. Unique information will be obtained on how galaxies evolve, on matter in extreme conditions, and on the life cycles of matter in the universe. In addition, new objects and phenomena unseen at higher frequencies are almost certain to be found, an exciting aspect of the ALFA mission. In addition to its very high potential for discovery, the ALFA mission will address several key issues in NASA's SEU science area, including: 1) understanding the evolution

of galaxies, 2) the exchange of matter and energy among stars and the interstellar medium, and 3) testing physical theories and revealing new phenomena. In each case, the key contribution of ALFA will be unprecedented angular resolution and sensitivity in a nearly unexplored frequency range. This gain in resolution and sensitivity will enable ALFA to detect and resolve individual objects anywhere on the sky and determine their low frequency spectra from imaging at multiple frequencies. As a result, ALFA will open up an entirely new regime of astrophysical investigation. Among the specific science objectives of ALFA are:

1) The evolution of galaxies

- Search for “fossil” radio galaxies to obtain information on the frequency and duration of the active phases of galactic nuclei, and on the intergalactic magnetic field.
- Search for very high redshift radio galaxies, which typically have steeper spectra than closer radio galaxies.
- Determine cosmic ray diffusion times away from galactic disks.

2) Life cycles of matter in the universe

- Accurately map diffuse interstellar ionized hydrogen, the last major component of the interstellar medium whose distribution is not currently well determined.
- Study the origin and transport of turbulence in the interstellar medium; constrain models for the dissipation of turbulent energy.
- Rigorously test the hypothesis that cosmic ray electrons originate in galactic supernova remnants.
- Map the 3-dimensional distribution of galactic low energy cosmic ray electrons to improve our understanding of cosmic ray transport and escape.

3) Test theories and reveal new phenomena

- Search for expected new sources of coherent radiation and determine the conditions in extreme plasma environments, including emission regions of millisecond pulsars.
- Test the diffusive shock acceleration model for the origin of cosmic rays; understand acceleration and energy loss processes in supernova remnants.
- Search for new sources of galactic nonthermal emission in supernova remnants, HI supershells (possible g-ray burst remnants), large-scale ionized filaments, the “galactic center fountain”, and presently unknown explosive remnants.

- Test the theory of coherent scattering of long- wavelength radio radiation by electrically charged dusty plasmas.
- Search for cyclotron emission from giant planets orbiting nearby stars.

How large a fraction of all galaxies had active nuclei in the distant past, but are now quiescent? ALFA can answer this fundamental question. The discovery of a significant number of "fossil" radio galaxies would provide important new constraints on galaxy evolution and specifically on the frequency and lifetime of active phases. Information on early epochs of galactic activity and its duration will help constrain models for the evolution of massive black holes in galactic nuclei. ALFA will search for fossil radio components associated with presently radio quiet galaxies (e.g., Goss, et al. 1987; Cordey 1987; Reynolds and Begelman 1997) as well as presently active galaxies to determine how often and for how long galaxies were active in the past. The long radiative lifetimes of electrons at low frequencies will preserve evidence of early phases of activity in galaxies which are too faint at higher frequencies to be included in existing radio catalogs. For example, a synchrotron source with an initial spectral index of -0.7 and 10^{-5} G magnetic field will have a spectral index of -2 above 3 MHz after ~ 0.4 billion years due to radiation losses. Such a source could have a flux density of 400 Jy at 3 MHz (easily detectable by ALFA) and yet be < 2 mJy at 1.4 GHz, below the detection limit of even the recent VLA Sky Survey (Condon, et al. 1998).

ALFA will expand the number of known galaxies at the highest redshifts. Extragalactic sources with steep spectra at low frequencies are typically high- z galaxies (e.g., Krolik and Chen 1991). ALFA is well suited to select the steepest spectrum sources from, for example, the 6C catalog at 151 MHz (Blundell et al. 1998), which are expected to be the most distant galaxies ($z > 4$). This distance limit increases with decreasing survey frequency, and consequently the ALFA sky survey will provide a glimpse of the Universe at a time when galaxies were young, possibly back to the protogalaxy era (Silk and Rees 1998). ALFA's observations of very distant galaxies will complement WIRE, FIRST, and SIRTf.

Ionized hydrogen is "the only major component of the interstellar medium that has not yet been surveyed" (Reynolds 1990). It is important to determine the large-scale distribution of diffuse HII both to improve our understanding of the heating and ionization processes in the interstellar medium and to account for the emission or absorption by this gas in other parts of the spectrum. ALFA will determine the galactic distribution of diffuse H II by measuring the free-free absorption of radiation along the lines of sight to a large number of bright galactic and extragalactic sources (e.g., Kassim 1989). Free-free absorption due to intervening ionized hydrogen produces a more steeply inverted spectrum below the turnover frequency than synchrotron self-absorption or internal free-free absorption, and thus the processes can be distinguished. These measurements by ALFA will cover high galactic latitudes, which are not well samples by pulsar dispersion measure observations, and can be combined with recent $H\alpha$ surveys. A critical question about the diffuse ionized medium is whether its energy comes from absorbing nearly all of the kinetic energy from stellar winds and supernovae or from radiation escaping from dense HII regions surrounding massive stars. The only way to answer this question is by mapping the distribution of diffuse HII with ALFA.

A better understanding of all aspects of interstellar scattering will tell us more about the turbulence properties of the interstellar plasma (energy input and transport) and consequently will shed light on its role in star formation and galactic evolution. ALFA can contribute to this goal in several ways. ALFA will map the distribution of scattering material by measuring the angular broadening of distant sources in all directions (e.g., Taylor and Cordes 1993), including high galactic latitudes. For paths which pass only through the diffuse “Type A” interstellar scattering medium (Cordes, Weisberg and Boriakoff, 1985) it will be possible to directly measure the inner scale of the turbulence. This is not possible with ground-based VLBI arrays operating at higher frequencies because the scattering disk is too small at these frequencies to resolve with Earth baselines. Only scattering by the clumpy “Type B” component of the interstellar medium is observable with ground-based VLBI. ALFA’s determination of the inner scale for Type A interstellar scattering will help identify the physical properties of the plasma responsible, and thus help understand heating of the diffuse interstellar medium by turbulent energy dissipation.

ALFA will test the hypothesis that cosmic ray electrons originate in galactic supernova remnants by directly detecting the presence of low energy electrons needed to initiate shock acceleration mechanisms. In addition, comparison of low and high frequency images of supernova remnants will allow spectral variations to be mapped, providing information on locations and efficiency of shock acceleration.

1.4. Discovery

ALFA will detect coherent radio emission from a wide range of objects by measuring their low frequency spectra and variability. Coherent emission processes, capable of producing extremely high brightness temperature radio emission, are common at long wavelengths. The sun, giant planets and Earth’s magnetosphere all display extremely strong coherent emission at low radio frequencies. As an example, below about 10 MHz electron-cyclotron maser emission from Jupiter is many orders of magnitude more intense than the incoherent synchrotron emission at higher frequencies. This type of emission (and the information it contains on local plasma and gyro frequencies) can only be detected and studied at low frequencies. Basic physics predicts that similar coherent processes will produce strong low frequency radio emission from objects such as supernova remnants, active galaxies, and quasars. In our galaxy, coherent emission is not only expected to occur and be detectable, but to be ubiquitous. The best way to identify coherent emission from objects outside the solar system will be based on their spectra measured by ALFA.

At present, pulsars and circumstellar masers are the only objects outside our solar system which are known to radiate coherently. At frequencies of a few MHz, however, many of the most intense discrete galactic sources in the sky (outside of the solar system) will be coherently-emitting sources driven by accretion and outflow. These are objects at the extremes of stellar evolution, with protostellar systems on one end and binary white dwarfs and neutron stars on the other.

Pulsars whose radio spectra have no observed low-frequency turnover, such as the Crab pulsar and some millisecond pulsars, are promising targets for ALFA. These pulsars will be among the strongest sources in the sky at frequencies below about 10 MHz (e.g., Erickson and Mahoney 1985). Timing data at higher frequencies provide an upper limit on the size of the coherent emitting region (Phillips and Wolszczan 1990) while measurement of a low-frequency spectral turnover by ALFA

will provide a lower limit. In this way ALFA will probe one of the most extreme environments known.

A large increase in low frequency radio brightness is also expected from coherent emission in relativistic jets (e.g., Baker et al. 1988; Benford 1992). This suggests that a much larger number of extragalactic objects may be detected by ALFA than would otherwise be possible.

ALFA will image galactic supernova remnants and other extended structures to search for new sources of nonthermal emission. For example, the question of whether the Crab nebula is located inside a previously undetected fast shock, as expected from mass and energy considerations, is still unresolved (Frail, et al. 1995; Sankrit and Hester 1997; Jones, et al. 1998). Because of its relatively steep spectrum, emission from the blast wave will be most easily seen at low frequencies. For the same reason, nonthermal emission associated with galactic features such as HI supershells (possibly remnants of previous gamma-ray bursts; Loeb and Perna 1998; Efremov et al. 1998), very old supernova remnants, the galactic center fountain, and large-scale ionized filaments (Haffner et al. 1998) will likely be found at the low frequencies measured by ALFA. Such emission contains information on the location and strength of shocks, and can allow very extended (old) remnants to be detected. A more complete sample of old explosive remnants provided by ALFA is essential to improve estimates of the frequency of supernovae and γ -ray bursts in our galaxy and the total kinetic energy input to the interstellar medium from explosive stellar events.

2. Mission Description

The “science instrument” for ALFA is the entire array of sixteen satellites operating together as an interferometer. Low frequency radio radiation will be sampled by a pair of orthogonal dipole antennas on each of the identical satellites, and each dipole will feed signals to a simple but flexible high dynamic range receiver. The dipoles are 10 m long, determined by the availability of self-deploying, flight-proven antenna elements. Observing frequency, bandwidth, sample rate, and phase switching of the receivers are controlled by the central spacecraft processor, and can be changed at will. The receiver is a straightforward, single channel design based on commercially available components. It covers 0.03-30.0 MHz, with Nyquist sampled bandwidths up to 125 kHz and an ability to handle a wide range of input levels. No new development is required.

ALFA will have a maximum baseline length of ~ 100 km, which provides a good over-all match to interstellar and interplanetary angular broadening. The array will be placed in a nearly circular distant retrograde orbit (DRO) about the Earth-Moon barycenter, with a typical distance from Earth of one million km. There are many advantages of a DRO for this mission, including sufficient distance from Earth to minimize terrestrial interference combined with the ability of each satellite to communicate directly with relatively small (11-meter) and affordable ground stations. Note that this approach involves no reliance on a single spacecraft for data relay or any other mission critical function; the array data path is extremely robust (16-way redundancy) all the way to the ground. Similarly robust is our technique for continuously monitoring the relative positions of the satellites by measuring the separations between all pairs of satellites. This provides far more constraints than are needed to solve for all of the relative positions. Should one or more of the array satellites fail, observing by the rest of the array continues unhampered.

ALFA will observe in all directions continuously, at frequencies determined by solar emission during solar radio bursts, and at one of several sky survey frequencies during periods between solar bursts. Each satellite receives an X-band carrier (to which the local oscillators are phase locked) and low-rate command telemetry, and transmits X-band data to the ground continuously at 0.5 Mb/s per satellite. The distance of the DRO and its location in the ecliptic plane allows continuous coverage of the array by three ground tracking stations. At the ground station telemetry headers are removed and the remaining interferometry data from each satellite are recorded on tapes for transport to the correlation computer. Small subsets of the data for rapid solar snapshot imaging will also be stored on disk and retrieved from the stations via internet. The DSN 11-m ground stations are currently operational, and operator intervention will be required only for occasional (once every several days) tape changes or in case of station equipment failure.

Among the challenges of imaging the sky at low radio frequencies is the need to image the entire sky at the same time. This is necessary because individual radio antennas of reasonable size have very low directivity at these frequencies (which is the motivation for using an interferometer array in the first place). Consequently very strong radio sources will create sidelobes in directions far from their positions, and high dynamic range imaging will require that the effects of strong sources be removed from all sky directions, not just from the region immediately adjacent to the sources. This in turn requires an array geometry which produces highly uniform aperture plane coverage in all directions simultaneously, a requirement that no previous interferometer array has had to meet. A quasi-random distribution of antennas on a single spherical surface was found to provide excellent aperture plane coverage in all directions with a minimum number of antennas. This concept was developed by Steve Unwin, who noted the importance of using a minimum separation constraint when computing antenna locations to avoid an excessive number of short projected spacings.

Cross-correlation of the signals will be done by Fourier transforming data from each satellite into a time series of frequency spectra and then cross-multiplying pairs of spectra to obtain the cross-power spectra for each baseline and for each phase center. The computing power required to cross-correlate all data in less than the observing time (3 GFLOPS) can be obtained from a cluster of workstations, for example eight Sun Ultra 60s. This approach offers greater flexibility and less cost than a dedicated hardware correlator, and will directly benefit from future workstation performance improvements.

Prior to cross-multiplication, all spectra will be multiplied by a combination of Gaussian and cosine functions to filter the frequency response of the array. This greatly reduces the delay beam sidelobes. The interferometer response is reduced below 1% when the geometric delay exceeds $21 \mu\text{s}$. For delays greater than $29 \mu\text{s}$ the interferometer response falls below 10^{-3} ; the maximum geometric delay of the array is about $330 \mu\text{s}$.

The delay-beam technique for suppressing interferometer response to emission far from the nominal phase center will fail for narrow-band signals. The most obvious source of narrow signals is terrestrial transmitters. This problem is minimized for ALFA by a combination of observing frequency selection, a high dynamic range receiver, ionospheric shielding, spectral data editing prior to cross-multiplication, and distance from Earth.

Phase calibration of the array is provided by the X-band uplink carrier, to which all satellite

oscillators are locked. Amplitude calibration is provided by: 1) periodically injecting a known calibration signal into the signal path between the antennas and low frequency receivers, 2) comparison with known astronomical sources at the high end of ALFA's frequency range, and 3) comparison with ground-based observations of solar bursts using antennas of known gain. The measured total power is iteratively divided between the fields of view, starting with the fields containing the strongest sources.

The array geometry is determined in two steps. First, the relative positions of all satellites are measured by on-board UHF ranging systems with an accuracy of better than ± 3 m. This gives the three-dimensional array geometry except for an over-all rotation, to which the inter-satellite ranging data are insensitive. Second, the orientation of the array in inertial space is determined by combining ground-based differential Doppler measurements (made simultaneously for all satellites) and the difference between predicted and measured changes in inter-satellite ranges caused by their slightly different orbital motion between station-keeping maneuvers. The angular orientation of the array will be determined to within half the highest-frequency fringe spacing every few days.

The theoretical array sensitivity at 3 MHz is ~ 10 Jy (1σ) in 5 minutes. The coherence time limits imposed by fluctuations in the solar wind do not prevent useful imaging even at the lowest frequencies (Linfield 1996). However, it will be confusion noise and dynamic range rather than the Galactic background which will determine the number of detectable sources. Confusion effects will be minimized by imaging all strong sources on the sky simultaneously so their flux can be taken into account for each field of view. Dynamic range is determined mainly by the number and distribution of visibility samples, the data signal-to-noise ratio, the quality of calibration, and the complexity of the sources being imaged. Based on our imaging simulations, we expect to obtain a dynamic range of $10^2 - 10^3$ for relatively compact sources (< 100 beams in size), depending on frequency. For very extended sources or the lowest observing frequencies the dynamic range will still be a few tens, which is entirely adequate for imaging strong, rapidly evolving sources. The use of linearly polarized dipole antennas is not a problem at very low frequencies because radiation will be depolarized by interstellar differential Faraday rotation across any source (Linfield 1995). Interplanetary differential Faraday rotation across the array will be negligible for solar elongations $> 90^\circ$, even at 1 MHz, and will also be averaged out for angularly large solar radio sources.

Aperture synthesis imaging of very wide fields requires 3-D Fourier transforms, but regions of limited angular size (over which the effects of sky curvature are small) can be imaged with separate transforms in which one dimension is much smaller than the other two (Cornwell and Perley 1992). This approach lends itself naturally to parallel processing. For ALFA the imaging problem is most difficult at the highest frequency (30 MHz) where the synthesized beam is smallest ($\approx 20''$). We plan to make 4096×4096 pixel images with 6 arcsecond pixels, so each image will cover an area of $6.8^\circ \times 6.8^\circ$. Thus, ≈ 1000 images are needed to cover the entire sky. Each image will require a 16 pixel Fourier transform in the "radial" direction to allow for sky curvature over the largest scale structure to which the data are sensitive. We will divide each image into ~ 100 smaller areas which will each be deconvolved with the appropriate synthesized or "dirty" beam (e.g., Frail, Kassim, and Weiler 1994). All clean components are subtracted from the data for each field and each field is transformed again to produce residual images. This process continues until no residual sidelobes remain.

The computing cost for each uncleaned image at 30 MHz is ~ 230 GFLOP, or less than 15 minutes on a Sun Ultra 60 workstation. A cluster of ten such workstations could produce an uncleaned all-sky image consisting of 1000 separate fields in a single day. At lower frequencies the synthesized beam is larger so fewer pixels (and consequently less time) will be needed for each image. Deconvolution of an all-sky image is expected to take 10-30 residual image iterations, or a maximum of 1 month for the worst case (30 MHz) on a workstation cluster. A large parallel machine of the sort available at JPL, NRL, and GSFC can reduce the time needed for deconvolution by up to two orders of magnitude.

Solar snapshot imaging will be much faster because 1) a smaller field of view is required, 2) the pixel size is generally larger, and 3) deconvolution may not be needed at all because solar radio bursts will be the strongest sources anywhere on the sky during active periods. Without deconvolution, a $20^\circ \times 20^\circ$ image centered on the sun at 1 MHz could be made in less than 5 minutes on a single workstation.

3. Conclusions

The progress made during the past years in solar system radio studies from individual spacecraft and in many areas of astrophysics from ground based interferometer arrays has largely covered large areas of the long-wavelength observational parameter space, whose dimensions are frequency, sensitivity, angular resolution, temporal resolution, and sky coverage. The region in this space least well covered by existing facilities is the combination of low frequencies, high angular resolution, and large sky coverage. This is the domain of space-based interferometer arrays. The first decade of the next century is likely to see the deployment of such instruments. When this happens, solar and planetary radio astronomers will be able to see the morphology of source regions, and galactic and extragalactic astronomers will have their first look at the low frequency sky with high enough resolution to distinguish large numbers of sources.

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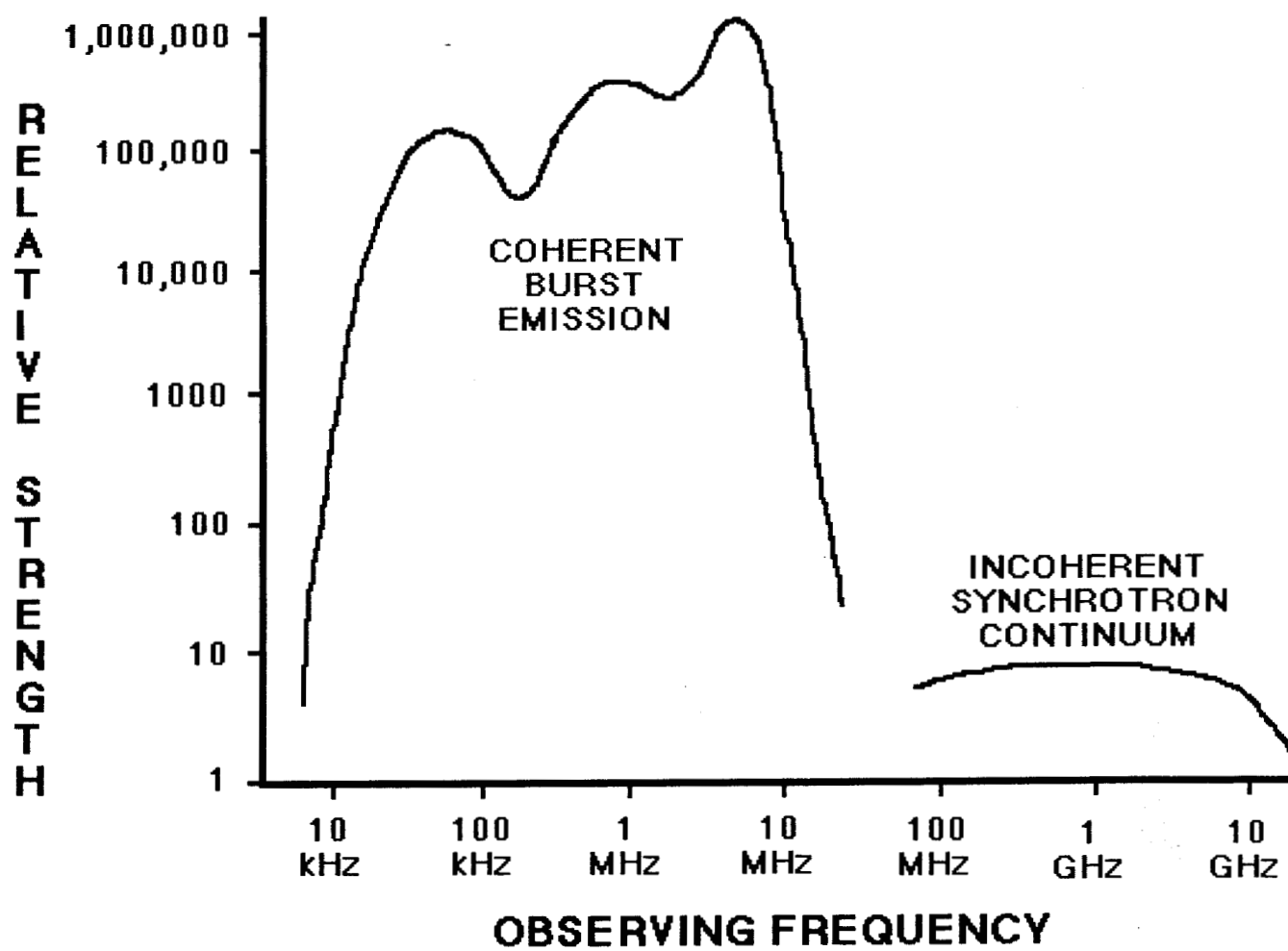
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FIGURE 1

FIGURE 2



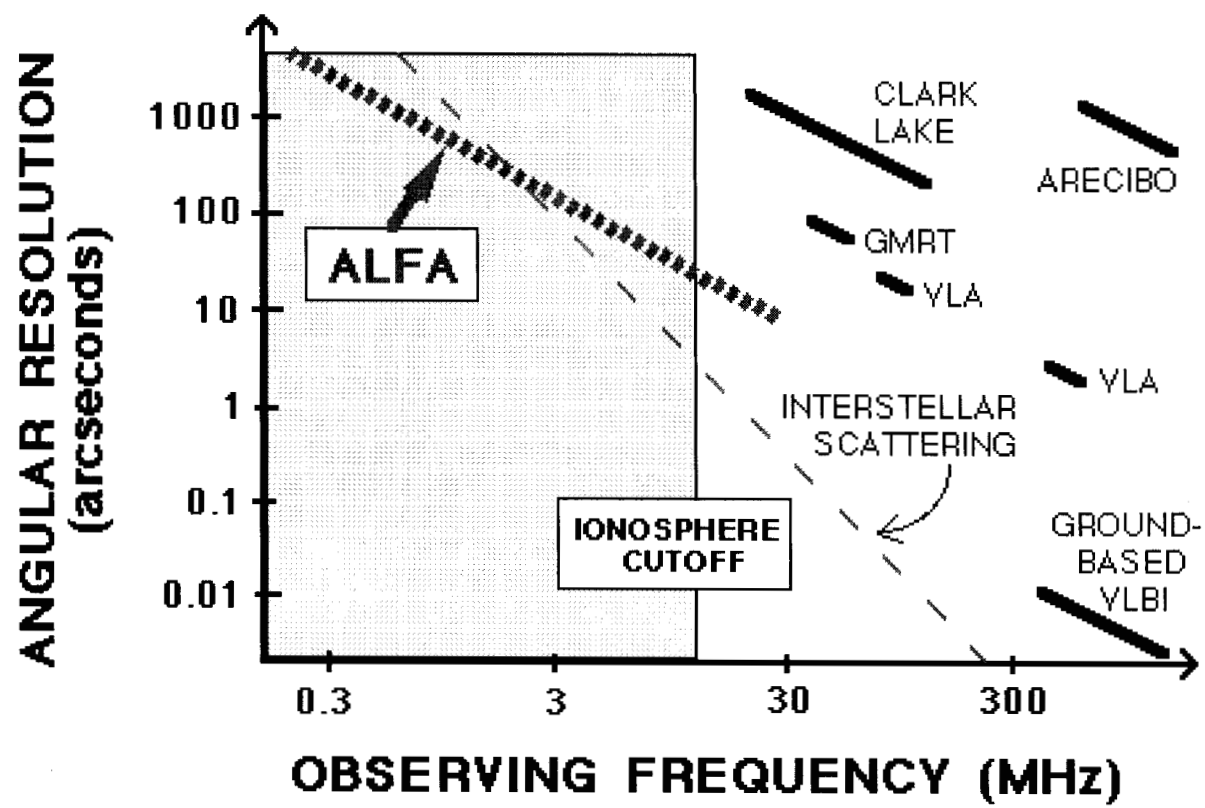
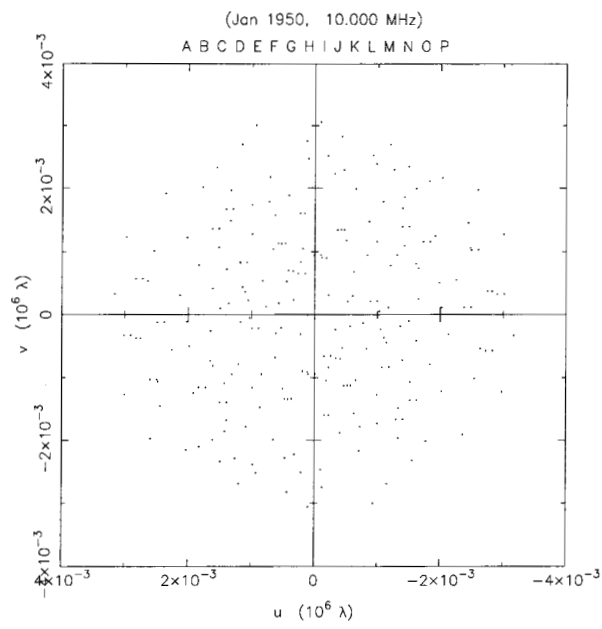
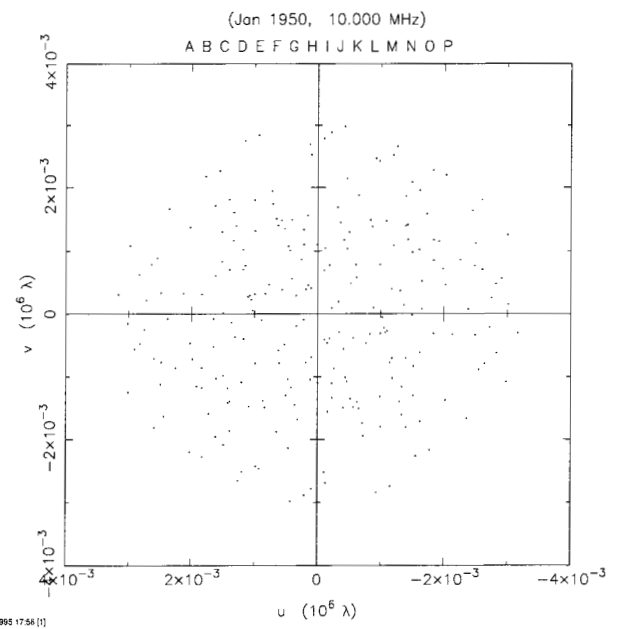


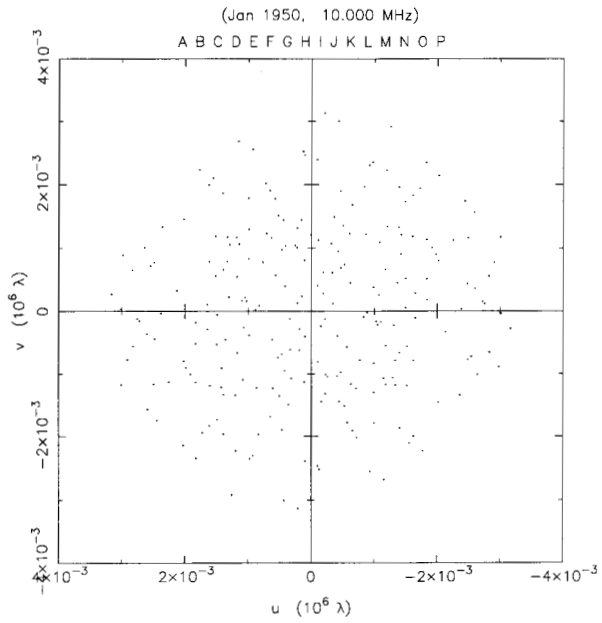
FIGURE 3



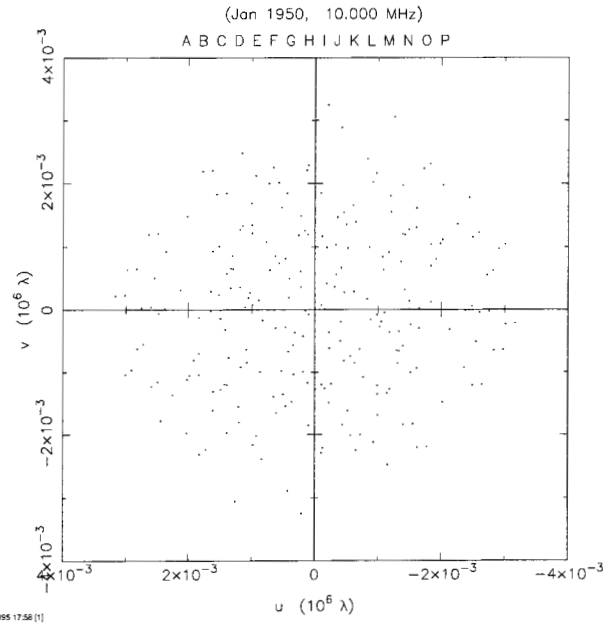
scu 14-Dec-1995 17:56 [1]



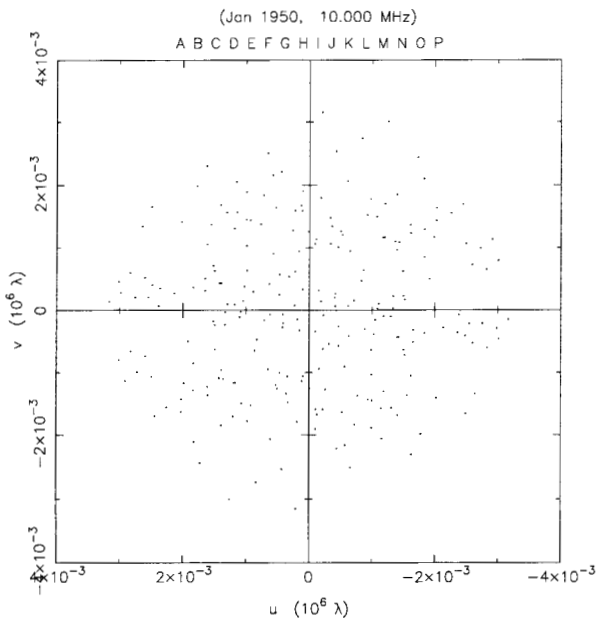
scu 14-Dec-1995 17:56 [1]



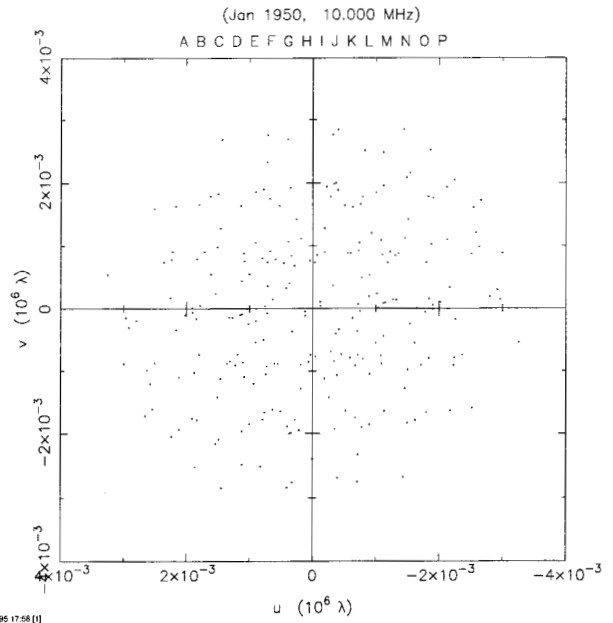
scu 14-Dec-1995 17:56 [1]



scu 14-Dec-1995 17:56 [1]



scu 14-Dec-1995 17:56 [1]



scu 14-Dec-1995 17:56 [1]

Figure 1: Array 15sn2 - (u, v) coverage for 0, 12, 24, 37, 53, and 90deg ecliptic latitude.

FIGURE 4

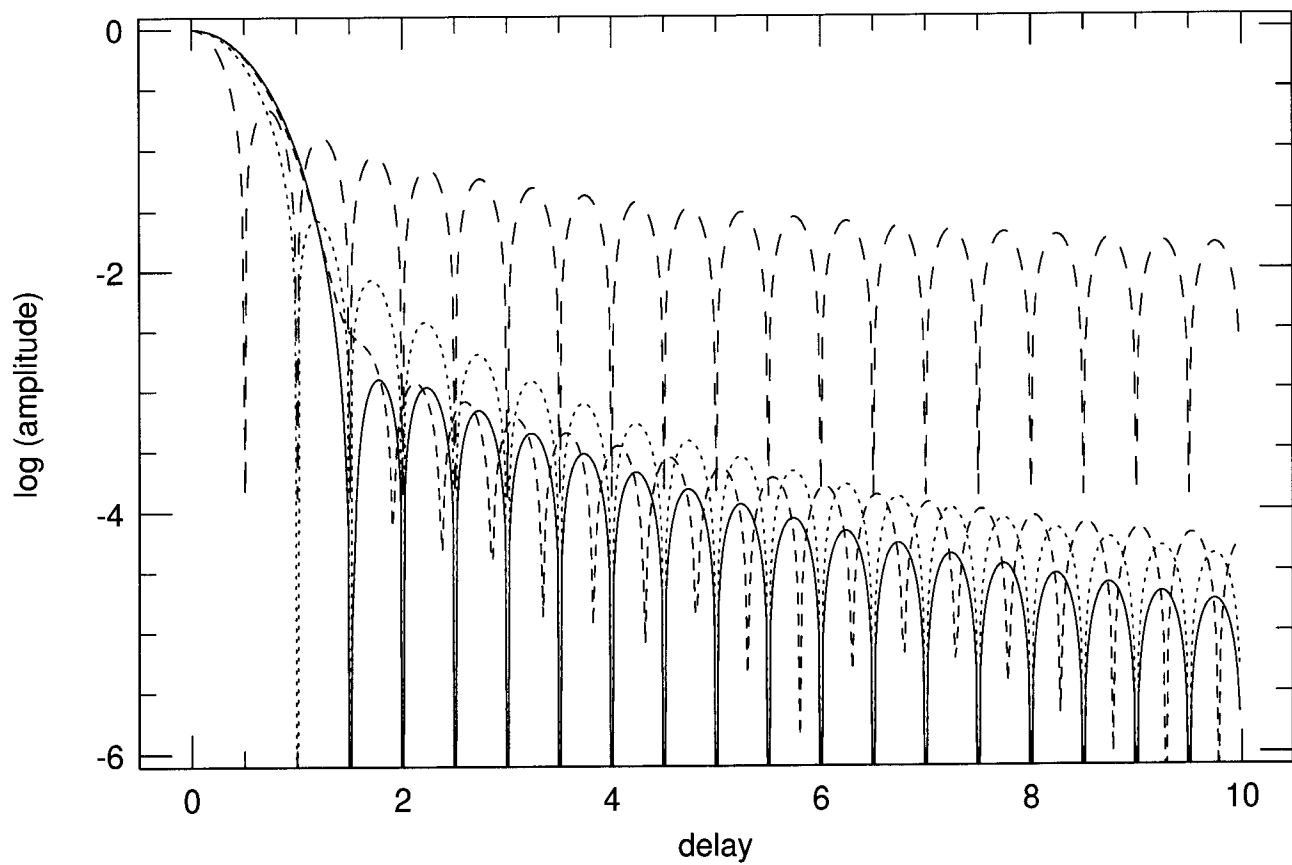
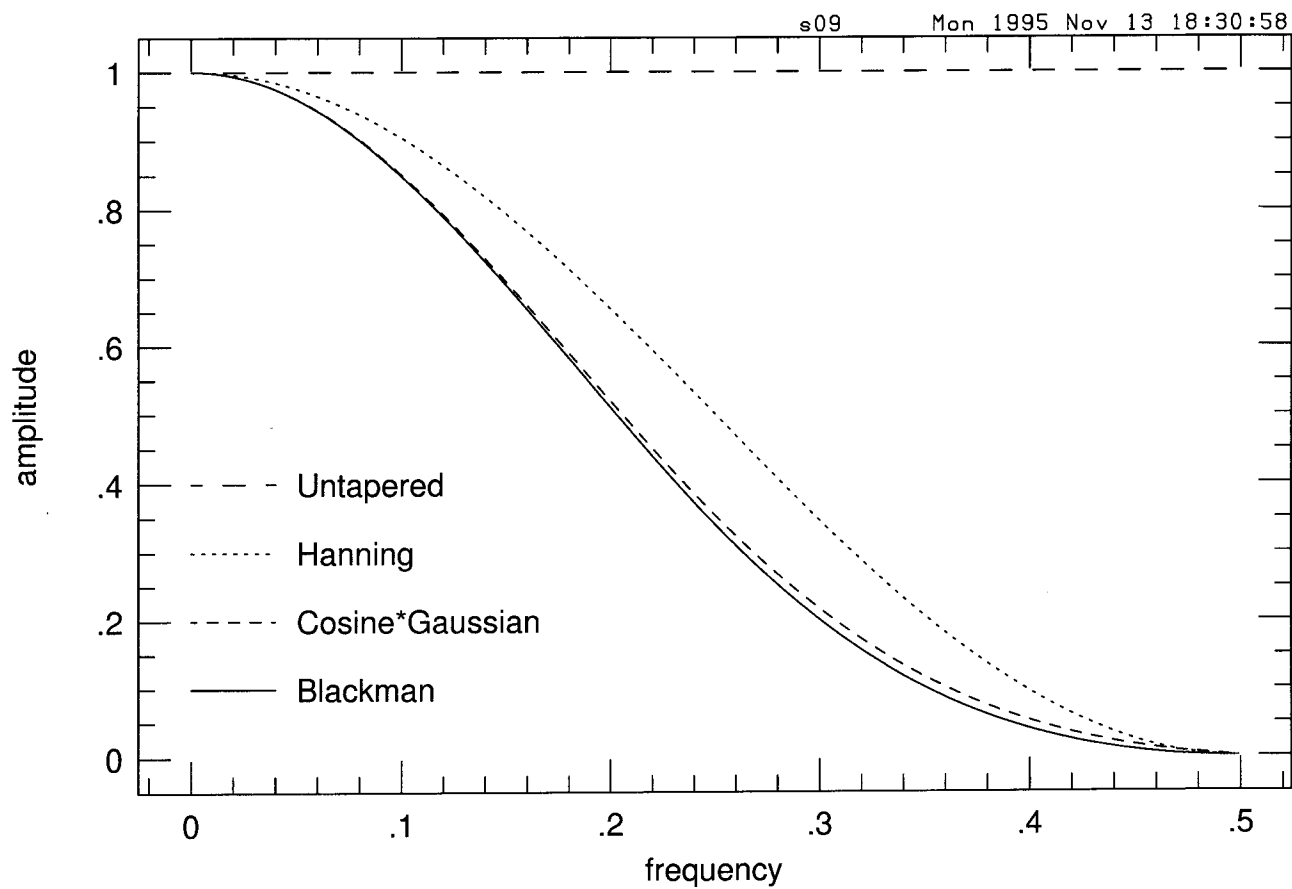


FIGURE 5